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Pliocene-Quaternary deformational structures in the eastern Algarve continental shelf, Gulf of Cadiz

Deformaciones pliocenas y cuaternarias en la plataforma continental oriental del Algarve, Golfo de Cádiz

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ABSTRACT

The eastern Algarve continental shelf in the northern margin of the Gulf of Cadiz has been investigated by analysing a set of high-resolution seismic reflection profiles. We examine the major structural elements affecting the upper sedimentary units. A seismo-stratigraphic interpretation and regional correlation allowed the identification of a major discontinuity that separates two main intervals, pre-Middle Pleistocene (MP) and post-MP. In addition, a number of deformation features such as ENE-WSW to NE-SW thrusts, kilometric-scale N-S to NW-SE folds and NNE-SSW to NNW-SSE sub-vertical normal faults were identified affecting the Pliocene-Quaternary sedimentary record, indicating neotectonic activity. The structures pre-dating MP are in agreement with a dominant transpressive regime along the continental shelf, under the Late Cenozoic NW-SE oblique convergence and related to the reactivation of Mesozoic diapiric structures. The structures post-dating MP induce a lower deformation of the sedimentary cover but were still active during the last glacial maximum, in agreement with the low uplift recognized in the Portuguese mainland.

Key-words: *Gulf of Cadiz, continental shelf, Pliocene-Quaternary deformation, seismic stratigraphy.*

RESUMEN

La plataforma continental del Algarve en el margen septentrional del Golfo de Cádiz ha sido investigada mediante el análisis de una red de perfiles sísmicos de alta resolución. Se presentan las principales estructuras que afectan a la cobertera sedimentaria superficial. Una interpretación sismoestratigráfica y correlaciones a nivel regional han permitido diferenciar dos intervalos separados por una discontinuidad principal, anterior y posterior al Pleistoceno Medio (PM). Los depósitos del Plioceno y Cuaternario están deformados por estructuras de deformación tales como cabalgamientos ENE-OSO a NE-SO, pliegues N-S a NO-SE de escala kilométrica y fallas subverticales NNE-SSO a NNO-SSE, que indican actividad neotectónica. Las estructuras anteriores al PM se generan en relación con el régimen transpresivo (NO-SE) dominante a finales del Cenozoico en esta región y la reactivación de las estructuras diapíricas mesozoicas observadas en el margen. En cambio, las estructuras posteriores al PM producen una ligera deformación de la cobertera sedimentaria y actividad durante el último máximo glaciar, lo que concuerda con un moderado levantamiento tectónico observado en la zona continental del margen portugués.

Palabras clave: *Golfo de Cádiz, plataforma continental, deformación pliocena-cuaternaria, estratigrafía sísmica.*

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Introduction

The Algarve margin is located in the northwestern sector of the Gulf of Cadiz, north of the Africa-Eurasia plate boundary. The Cenozoic tectono-stratigraphic evolution of the margin is linked to the geodynamic evolution of the Gulf of Cadiz and the Betics-Rif (Fig. 1A), where the convergence between Africa and Eurasia played an important role (*e.g.*, Terrinha, 1998; Ramos *et al.*, 2016, among others). The stratigraphic evolution of the margin during the Pliocene and Quaternary was characterised by the development of turbidites, contourites and hemipelagic deposits driven by long-term tectonic processes and short-term climatic/eustatic changes (*e.g.*, Hernández-Molina *et al.*, 2016). Fault activity and important seismicity have also been documented in the margin during that interval (*e.g.*, Ressurreição *et al.*, 2011; Cabral, 2012). However, this tectonic evidence is scattered and fragmented in the continental shelf. In this sense, the aims of this work are to characterise and analyse the deformational structures on the eastern Algarve continental shelf and their connection to its Pliocene-Quaternary tectono-sedimentary evolution. To reach these goals, we have interpreted a set of high-resolution seismic reflection profiles. Age constraints are obtained through the correlation of the seismic grid with IODP Expedition 339 sites collected on the middle slope.

Geological setting

The regional geology of the Algarve comprises Palaeozoic basement rocks and a flysch sequence of slates and greywackes dating back to the Hercynian orogeny in the northern emerged area; the so-called Algarve Basin extends from the onshore to the offshore southern area and contains Mesozoic and Cenozoic sedimentary rocks (Fig. 1A, B). The Mesozoic rocks include continental siliciclastics and marine carbonates deposited in a Late Triassic proto-basin due to the break-up of Pangea. Evaporites were subsequently deposited during the early phase of rifting in the earliest Jurassic. The Cenozoic record is mainly composed of marine carbonates and siliciclastic sediments (Terrinha, 1998).

They were deposited in a flexural basin related to the Betics-Rif evolution, the Gulf of Cadiz accretional wedge and the Neogene basins (*e.g.*, Gràcia *et al.,* 2003).

The structural style of this region was dominated by extensional faulting and diapirism during the Mesozoic (Terrinha, 1998; Matias *et al.,* 2011). The formation of the Betics-Rif orogen from early Miocene onwards led to a tectonic inversion process, causing a regional uplift evidenced by an erosive coastal unconformity between the Lower Cretaceous and overlying Miocene strata (Terrinha, 1998). Offshore, local inversion of pre-existing Mesozoic faults and salt-related structures has been documented (Ramos *et al.,* 2016). More stable conditions dominated the Algarve margin during the late Miocene to the Quaternary. Tectonic activity has been a main factor controlling the margin sedimentary stacking pattern while climate and relative sea-level changes have impacted at shorter timescales (Hernández-Molina *et al.*, 2016). However, ongoing diapiric and fault activity have also been documented (Matías *et al.,* 2011; Cabral, 2012).

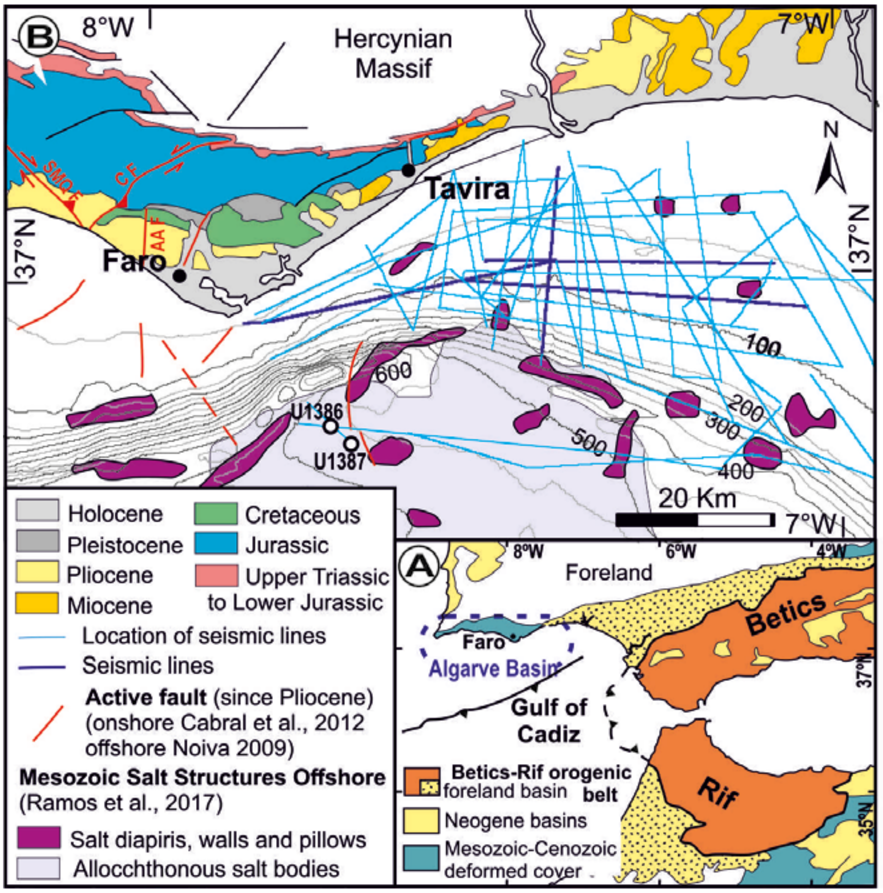

Fig 1.- A) Main tectonic domains of the Betic-Rif Orogen and associated Neogene basins. B) Study area location and geological map (modified from Rodríguez-Fernández *et al.,* 2015) and the sites IODP Exp. 339 (U1386, U1387); SMQF: San Marcos-Quarteira fault; CF: Carcavai fault; AAF: Areias de Almarsil fault. See color figure in the web.

Fig 1.- A) Mapa tectónico general del Orógeno Bético-Rifeño y de las cuencas neógenas asociadas. B) Mapa geológico (modificado de Rodríguez-Fernández et al.*, 2015) con la localización del área de estudio y de las perforaciones de IODP Exp. 339 (U1386, U1387); SMQF: falla de San Marcos-Quarteira; CF: falla de Carcavai; AAF: falla de Areias de Almarsil. Ver figura en color en la web.*

Database and methodology

This study is based on the interpretation of different types of seismic data: i) high-resolution Uniboom profiles and ii) high to medium resolution Sparker seismic profiles. The maximum penetration is estimated to be 160-165 m (200 ms) and 240-247.5 m (300 ms) respectively, assuming an average velocity of 1600-1650 m/s for the Pliocene-Quaternary sediments, with a metric-scale vertical resolution. These datasets have been collected on the continental shelf between Faro (Portugal) and the Guadiana River mouth during the FADO 96, WADIANA 2000, COMIC 2013 and LASEA 2013 surveys, which form a network of 77 reflection seismic profiles, covering an area of 765 km^2 (Fig. 1B). The interpretation procedure included the following steps: i) compilation of all available data in IHS Kingdom Geosciences software; ii) picking of the major seismic horizons and regional correlation; iii) identification and mapping of the main neotectonic features; iv) age attribution of seismic horizons through the correlation of the seismic grid with sites U1386 and U1387 (Fig. 1B) drilled during IODP expedition 339 (Hernández-Molina *et al.,* 2016; Mestdagh *et al.,* 2019).

Results and interpreted structures

Seismic stratigraphy

We use a major regional seismic discontinuity representing a depositional hiatus between 0.3 – 0.9 Ma (see Figs. 2, 3A and B) along the inner shelf as a stratigraphic marker. This hiatus is formed by the overlap of two erosional truncation surfaces, respectively labelled LQD (~ 0.3 – 0.6 Ma) and MPD (~ 0.7 – 0.9 Ma), of assumed late Quaternary and Middle Pleistocene age, (Hernández-Molina *et al.,* 2016), as shown in figure 2. These discontinuities are identified in the outer shelf areas near the upper slope and merge landward increasing the depositional hiatus and defining the most evident unconformity labelled LQD+MPD. This combined discontinuity divides the sedimentary record into two intervals, pre-Middle Pleistocene (pre-MP) and post-Middle Pleistocene (post-MP).

The pre-MP record exhibits a wedge-shaped geometry thickening toward the south-southeast (Fig. 2). It is composed of deformed reflections dipping mostly toward the southeast, which usually show erosional truncations to toplap geometries, abutting against the main upper discontinuity LQD+MPD (Fig. 3A, B). The post-MP record is characterised by continuous subparallel reflections with several internal sub-units bounded by minor erosional truncation surfaces, of which the youngest and most prominent one is related to the last subaerial discontinuity (LSD) associated with the Last Glacial Gaximum–LGM (~ 0.02 Ma, Lobo *et al.,* 2018). This surface exhibits a variable morphology, with planar and rugged erosional truncations (Figs. 2, 3A and B). High paleoreliefs of the pre-MP record cause the LSD to rework the main discontinuity (LQD+MPD) at specific inner shelf sites. Thus, locally an erosional surface spans a major hiatus from ~ 0.9 to 0.02 Ma (Fig. 3B).

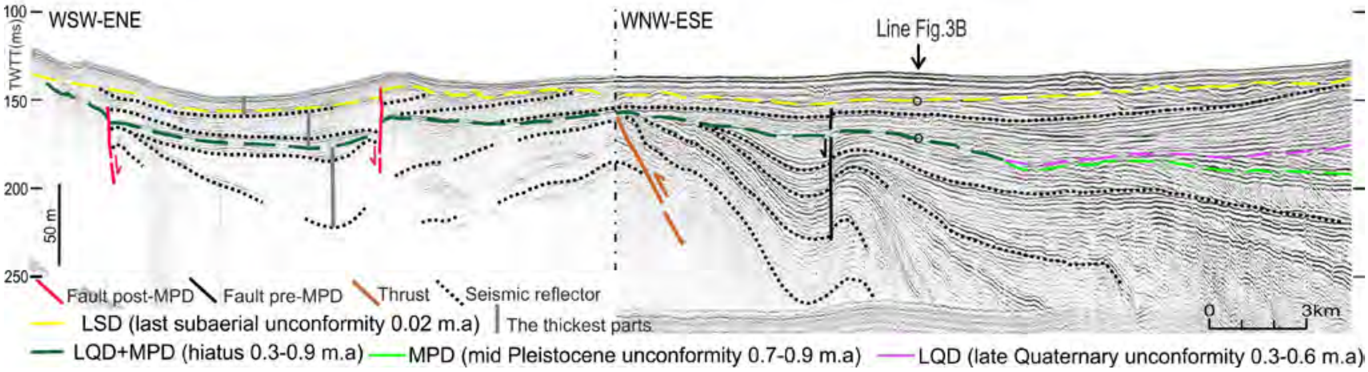

Fig. 2.- E-W composite seismic profile interpreted along the study area. Profile location given in figure 3C. See color figure in the web.

Fig. 2.- Composición de un perfil sísmico E-O interpretado a lo largo del área de trabajo. Localización en la figura 3C. Ver figura en color en la web.

Deformational structures

We observe different types of deformational features with tentative ages based on their relationship to the inferred chronology with the major discontinuities.

i) Structures pre-dating the Middle Pleistocene Discontinuity (MPD).

The LQD+MPD discontinuity truncates a number of shortening structures including thrusts, folds and faults in the pre-MP deposits (Figs. 2, 3A and B). Thrust surfaces are inferred from the shape of the deformed reflections where footwall ramps geometries are recognized (Fig. 2). They are localized over the middle shelf with ENE-WSW to NE-SW directions and dipping basinward (Fig. 3C). Two ENE-WSW striking thrusts show lateral continuity up to 7 km, whereas the widths of the thrust slices reach about 5 km in plan view. Kilometric-scale, N-S to NW-SE folds (Fig. 3C) with superimposed paleochannel morphologies are recognized in E-W seismic lines (Fig. 3A). The folds show non-cylindrical geometries, with broad synclines and acute anticlines. The anticline limbs are cut by kilometric-scale vertical normal faults subparallel to the fold axial traces (Fig. 3A, C).

ii) Structures post-dating the Middle Pleistocene Discontinuity (MPD).

Two NNE-SSW to NNW-SSE directed sub-vertical faults showing a main normal movement are identified on the western sector of the middle shelf (Fig. 2). Both faults are planar fractures with drag folds in the relative sinking block. They cut pre and post-MP deposits, and consequently also the shortening structures (syncline limbs) and the LQD+MPD discontinuity. These faults exhibit a maximum vertical displacement of 8 m, decreasing to zero at the top of the fault (Fig. 2), which is typical for syn-sedimentary faulting (Childs *et al.*, 2003). Sediment thickness along the WSW-ENE line shown in figure 2 suggests a gradual westward migration of depocenters that could be indicative of the occurrence of strike-slip movements along the faults (*e.g.*, Noda, 2013). The easternmost fault close to Tavira was still active during the LGM.

Discussion and Conclusions

Around the study area, different evidences indicate the reactivation of pre-existent faults during the Pliocene-Quaternary (Cabral, 2012). Most of these faults have been reactivated as strike-slip faults with reverse component (Terrinha, 1998; Ressurreição *et al.,* 2011), such as the onland NW-SE San Marcos-Quarteira (SMQF) and the NE-SW Carcavai (CF) faults (Fig. 1B). The possible offshore prolongation of these faults has been deduced from coastal sediment deformation of Miocene-lower Pliocene age (Noiva, 2009). Additionally, the regional Cenozoic shortening of the margin has also caused the activation of Mesozoic salt structures (Fig. 1B). In fact, halokinetic processes deforming the Pliocene-Quaternary strata are still active in the Algarve Basin (Matias *et al.,* 2011; Ramos *et al.*, 2017).

In this context, the structures predating the MPD recognized in the study area, such as the ENE-WSW to NE-SW thrusts with a northwestward transport direction, are likely a consequence of the regional geodynamic conditions dominated by the NW-SE convergence of Africa and Eurasia in the Gulf of Cadiz since the Tortonian. In addition, the N-S acute anticlines may be related to the reactivation of Mesozoic salt structures (diapirs) in the vicinity of the study area (see Fig. 1B). Such a reactivation may cause the folding of strata with the generation of crest faults on top of halokinetic structures, thus affecting the pre-MP deposits and the deformation of east-west thrust planes. These crest faults could still have been active during the Middle Pleistocene (Fig. 2).

In the western part of the study area, NNE-SSW to NNW-SSE faults postdating the MPD are shown to have been active during the last glacial cycle (Fig. 2). Active faults with the same orientation have been identified onshore (*e.g.,* the Areias de Almarsil fault) and offshore close to Faro (Noiva, 2009; Cabral, 2012). In addition, two major regional structures (the SMQF and CF) have shown activity during the last 3 Ma (Cabral, 2012, see also figure 1B). These younger faults have both vertical and strike-slip movement components, in agreement with the regional neotectonic activity evidenced by the almost uniform uplift of the Portuguese mainland territory since the end of the Pliocene (Cabral, 2012).

This study integrates a seismic stratigraphic interpretation with an analysis of tectonic structures on the eastern Algarve shelf to improve the understanding of the Pliocene-Quaternary tectonic evolution of the northern Gulf of Cadiz continental margin. A major angular discontinuity separates two distinctive tectonic phases: i) a pre-MPD transpressive phase (previous to 0.9 Ma), with shortening structures (ENE-WSW thrusts and N-S folds), associated with the post Tortonian convergence and linked to the reactivation of salt structures in the eastern Algarve basin, and ii) a post-MPD phase (0.9 Ma to the present), which is mainly characterized by alternating erosional-depositional patterns and minor deformations related to slow slip rate active faults, associated with vertical crustal movements.

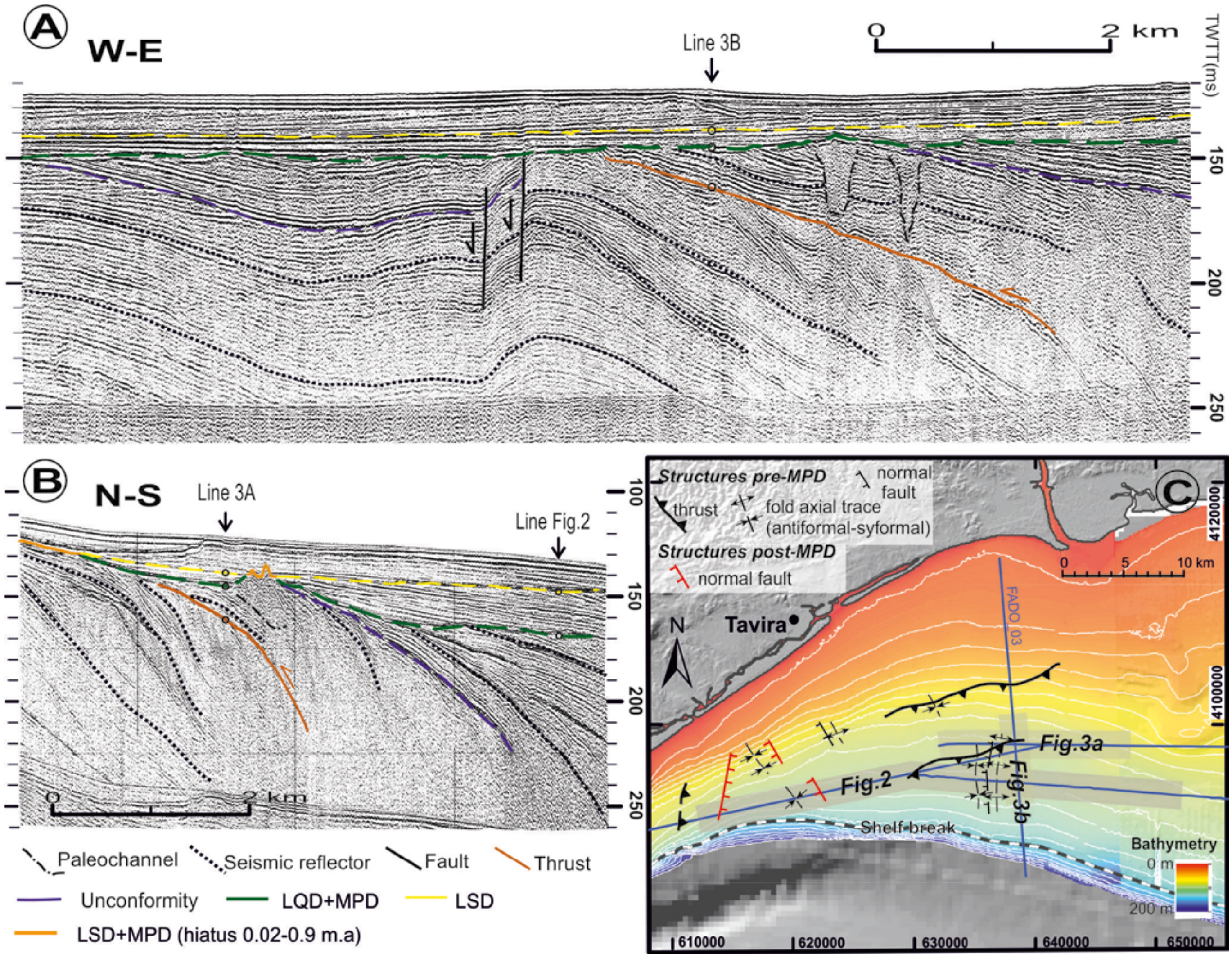

Fig. 3.- A) W-E seismic section interpreted. B) N-S Seismic section interpreted. C) Detailed structural mapping of the study area and location of the section lines shown in figures 2, 3A and 3B. See color figure in the web.

Fig.3.- A) Sección sísmica O-E interpretada. B) Sección sísmica N-S interpretada. C) Mapa estructural detallado del área de estudio con la localización de las secciones sísmicas de las figuras 2, 3A y 3B. Ver figura en color en la web.

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